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PROBLEMS OF EARTH PRESSURE ON SUBTERRANEAN STRUCTURES IN USSR AND PLANNING OF SOVIET BOMB-PROOF SHELTERS

Ch'en Ying-chun

/Figures are appended./

This study is based on a textbook used by the Soviet Army on the subject of field fortifications, depressed roads, concealed trenches, trenches for protection against air raids, and other underground construction. The Soviet textbook was based on an article, translated by Harada Senzo, which appeared in the May 1943 issue of the magazine of the Japanese Civil Engineering Society. This translation of the material in the Soviet Army textbook is published here for reference by interested parties. From this it is possible to learn of the theory of earth pressure used by the USSR when planning underground construction, and to understand something of USSR research on the depth of chambers that are to be safe from artillery and aerial bombardment. The article also throws light on the investigation of the ability of tunnels and other underground chambers to withstand explosions.

A. Earth Pressure on Underground Structures

When an excavation is made, the solidarity of the mass is broken and the forces in the ground surrounding the excavation are changed. Due to this, the ceiling and sides of the chamber are apt to bulge downward or inward and the earth tends to fall down or develop cracks; sometimes the earth collapses completely.

To avoid such an occurrence and preserve the solidarity of ground around the excavation, it may be necessary to erect lining walls, or supporting columns or posts. With respect to the forces exerted on the lining walls or supporting columns, their strength and direction depend largely on such factors as the composition of the earth, its hardness and density, its lay, and degree of moisture. For instance, the weaker the cohesion of soil particles, the greater the pressure /on the lining, or columns/.

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To determine the dimensions required for columns and/or lining walls, it is first necessary to know the pressure. The pressure may be ascertained by experiment with considerable accuracy, although such tests would require a comparatively long time, and are not practicable in time of war. Hence it is necessary to rely on theoretical calculations. Both the vertical and horizontal pressures must be calculated, and these will be dealt with separately below.

1. Vertical Pressure

There are several theories concerning vertical pressure. The two principal ones are: (a) the vertical pressure on an underground chamber is directly proportional to its depth below the surface, i.e., to the weight of the earth superimposed on the ceiling of the chamber; (b) there is no necessary relationship between the depth of the chamber and the degree and nature of the pressure of the superimposed earth. Only a portion of the volume of earth within the limits of a given arch exerts pressure. The shape of the arch must depend on the physical and mechanical characteristics of the material and the dimensions of the chamber.

For underground military defense chambers in general, the second theory is applicable; while the first is applicable for chambers near the surface and/or where the earth is friable and weak. The second theory should be used for calculating the vertical pressure on all underground field defense works which are to be more than 10-12 meters below the surface, and to have excavated chambers less than 2.5 meters wide.

The second of the above-mentioned theories, which is supported by Professor P. D'yakonov, is generally employed in the USSR. In accord with this theory, when underground excavations are being made, due to the redistribution of forces that takes place in the earth above the chamber, the roof or ceiling tends to take the shape of a natural arch which then carries the pressure which is above it. The earth inside the arch is disturbed and there is danger that it will collapse. The shape of a natural arch is that of a parabola, whose height may be expressed as

$$h = \frac{a}{f} \qquad (1)$$

where a equals one half of the width of the cross section of the excavation in meters; f equals the coefficient of consistency of the earth (see Table 1). In the case of friable earth, f equals tangent ϕ, where ϕ equals the internal angle of friction of the earth layer.

Table 1

(f represents the coefficient of consistency, density and hardness, of the earth layers; r represents the specific weight of the mass of earth concerned, in tons per cubic meter; ϕ represents the internal angle of friction.)

No	Rough Classification of Consistency	Kinds of Earth Layers	f	r(t/cu m)	ϕ
1	Greatest hardness	Fine-grained quartz and basalt	20	2.9	87°
2	Very great hardness	Very firm and hard granite, porphyritic rocks; very hard schistose siliceous rocks, but less hard than No 1 quartz; very hard sandstone and limestone	15	2.6	85°

No	Rough Classification of Consistency	Kinds of Earth Layers	f	r(t/cu m)	Ø
3	Firm and hard	Granites and granitic earth strata; hard sandstone and limestone; quartz veins or dike rock; dense hard conglomerates; very dense hard iron ore	10	2.6	82°30'
4	Firm and hard	Hard and firm limestone; not very solid and hard granite; firm sandstone, firm marble; dolomite; iron pyrites	8	2.7	80°
5	Comparatively solid and hard	Ordinary sandstone; iron ore	6	2.4	75°
6	Comparatively solid and hard	Sandstone schist; schistose sandstone	5	2.5	72°30'
7	Medium strata	Argillite or clay state; not firm and hard sandstone and limestone; comparatively soft conglomerates	4	2.8	70°
8	Medium strata	Not very firm laminated rocks; mediumly dense marl	3	2.5	70°
9	Comparatively soft	Soft slatey rock; soft limestone; rock salt, gypsum, frozen earth; smokeless coal; ordinary marl; disintegrated sandstone, conglomerates, and gravel; boulders and earth mixtures	2	2.4	65°
10	Comparatively soft	Gravel and earth mixtures; disintegrated slate, old deposits of fragmented rocks; hard coal (1.4-1.8); hard clay	1.5	1.8-2.0	60°
11	Soft	Fine and dense clay; medium coal (1.0-1.4); firm alluvial soil, clayey earth	1.0	1.8	45°
12	Soft	Light sandy clay; loess; pebbles, soft coal (f equals 0.6-1)	0.8	1.6	40°

No	Rough Classification of Consistency	Kinds of Earth Layers	f	r(t/cu m)	Ø
13	Soil	Soil of vegetable origin; peat; light sandy clay; damp sand	0.6	1.5	40°
14	Easily friable	Sand; soft stone fragments; loose earth	0.5	1.7	37°
15	Mud	Mire; slimy mud (dredged from canals and used for enriching nearby cultivated land); water-bearing loess; other wet earths or soils	0.3	1.5-1.8	9°

When making excavation of an underground chamber in a horizontal direction, as the cross section is widened, there is a tendency for the earth overhead to collapse. The shape of the upper part, as shown in Figure 1, tends to take the form of a parabola. The angle between a horizontal line and the slope of an exposed surface of friable earth just before collapse is called the internal angle of friction.

Figure 2 indicates that the base line of the overhead parabola is at the intersection of the plane of the exposed side slopes with the roof of the excavated chamber. This parabola is called the collapse arch.

The height, h_2, of the collapse arch is

$$h_2 = \frac{a_2}{f}. \qquad (2a)$$

In this formula a_2 is one half of the span of the collapse arch.

$$a_2 = a + b \tan (90 - Ø)$$

where a equals one half the width of the cross section of the chamber being excavated, in meters, and b equals the height of the excavated chamber, in meters. Substituting these equivalents in Formula (2a) we have

$$h_2 = \frac{a + b \tan (90 - Ø)}{f}. \qquad (2b)$$

Where the sides of the excavated chamber are walled up with a [vertical] lining, the angle between the [vertical] surface of the wall and the slip surface behind it, is $45^\circ - \frac{Ø}{2}$, and in the area limited by the slip surface a side thrust is generated. Over the excavated chamber there is formed a pressure arch, and the weight of the material inside the pressure arch [and outside the natural arch] creates pressure on the lining wall. The height of the pressure arch, h_1, is

$$h_1 = \frac{a_1}{f}, \qquad (3a)$$

where a_1 is half the span of the pressure arch in meters. Then

$$a_1 = a + b \times \tan (45 - \frac{Ø}{2}).$$

Putting these values in our equation, we have

$$h_1 = \frac{a + b \times \tan(45 - \frac{\phi}{2})}{f}. \qquad (3b)$$

If the vertical force (weight) of the earth is uniformly distributed on the lining wall, the pressure, q, is equal to

$$h_1 \times r \times 1 \qquad (4)$$

where r is the specific weight of the earth, in tons per cubic meter.

Example: Let the width of the chamber to be excavated, 2a, be 2.3 meters, and the height of the chamber, b, be 2.3 meters. Calculate the height of the pressure arch, h_1, and the vertical pressure on the lining wall of an underground chamber. The soil is of the clayey type whose specific weight r is taken as 1.8 t/cu m, its internal angle of friction Ø as 40 degrees, and its consistency f as 0.84.

Solution: The height of the pressure arch, h_1, according to Formula (3b), is

$$h_1 = \frac{a + b \tan(45 - \frac{\phi}{2})}{f}.$$

Substituting the given values in this equation, we have

$$h_1 = \frac{1.15 + 2.3 \times 0.47}{0.84} = 2.65 \text{ m.}$$

The vertical pressure of the earth, q, according to Formula (4) is

$$q = 2.65 \times 1.8 \times 1 = 4.77 \text{ t/sq m.}$$

2. Horizontal Pressure

For ascertaining horizontal pressure, we may use Coulomb's method, which gives the pressure of adjacent earth against its retaining wall. If the earth has the same characteristics as in the preceding case, then the pressure diagram will be as shown in Figure 3, where e_2 is the horizontal pressure at the bottom of the excavation and e_1 is the pressure at the level of b meters above the bottom, as indicated in the ladder-type diagram of Figure 3.

$$e_1 = h_1 \times r \times \tan^2(45 - \frac{\phi}{2})$$

$$e_2 = (h_1 + b) \times r \times \tan^2(45 - \frac{\phi}{2}) \qquad (5)$$

In these equations, h_1 is the height of the pressure arch; b is the height of the cross section to be excavated; r is the specific weight of the contiguous earth; Ø is the internal angle of friction.

The computation of the lateral pressures on the sides of a deep vertical excavation is to be made by the same method as in the case of a retaining wall. In Figure 4a, let a be a point at the depth H below the surface of the ground, and assume the soil to be homogeneous in consistency. Then the pressure at the point a is

$$e_a = H \times r \times \tan^2 (45 - \frac{\emptyset}{2}). \qquad (6)$$

In Figure 4b, let the soil consist of n layers of unlike consistencies of earth. The lateral pressure at the level e_n is found by use of the following formula:

$$e_n = (y_1r_1 + y_2r_2 + \dots\ y_{n-1}r_{n-1} + y_nr_n) \tan^2 (45 - \frac{\emptyset}{2}). \qquad (7)$$

In this equation, e_n is the lateral pressure at the depth C; y_1, y_2, y_3,... y_{n-1}, y_n, are the thicknesses of the respective layers of earth; r_1, r_2, r_3,... r_{n-1}, r_n, are the specific weights of the various layers of earth; $\emptyset_n$ is the internal angle of friction of the soil of layer n.

Example: Find the lateral pressure, e_1, (Figure 4a), at the top of the excavated chamber, and at e_2 at the bottom.

Solution: From Formula (5),

$$e_1 = 2.65 \times 1.8 \times (0.47)^2 = 1.054 \text{ tons/sq m}$$

$$e_2 = (2.65 + 2.3) \times 1.8 \times (0.47)^2 = 1.968 \text{ tons/sq m}$$

The total lateral pressure on one side of the chamber [for a section one unit thick] is

$$E = \frac{(e_1 + e_2)}{2} \times b = \frac{(1.054 + 1.968)}{2} = 3.475 \text{ tons.}$$

B. Determination of Protective Thickness of Underground Structures

The protective thickness of earth against artillery shells and aerial bombs for underground chambers is the distance from the surface of the ground to the top or roof of the excavated chamber. The chamber itself, for safety, must be located at a depth below the surface greater than this distance. The soils in which underground defense chambers may be built are divided into three main types having three different coefficients of consistency (see Table 1): (a) firm or solid earth, (b) loose earth, and (c) rock. The types of soils where the building of an underground chamber is contemplated should be ascertained. Separate consideration will be given, first, to cases where the soil is homogeneous and, second, to where it is not homogeneous.

1. When the chamber is to be made in firmly compacted earth (coefficient of consistency, f equals 1 to 4), the depth, or thickness of the protective layer of earth required will depend on a combination of two factors; the penetration of the shell or bomb, and the explosive power or blasting effect of the projectile. The depth below the surface of the top of the pressure arch must be greater than the maximum depth of penetration of the projectile plus its explosive effect. Figure 5 permits us to write the following formula:

$$H_1 = h_y + r_p + h_1 - u, \qquad (8)$$

where

H_1 = total protective thickness
H_y = the depth of penetration of the projectile
r_p = radius of the projectile's explosive effect
h_1 = height of the pressure arch
u = distance of the center (core) of the projectile to the point of deepest penetration below the ground surface

2. When the chamber is to be made in loose earth (coefficient of consistency, f equals less than 1; see Table 1), the height of the pressure arch is not taken into consideration; but the depth of the top of the excavation must have a margin of safety beyond the depth of the projectile's penetration, plus the radius of its explosive effect. The reason for ignoring the height of the pressure arch, and substituting a margin of safety instead, is that with loose friable soil, the height of the pressure arch would be very great and, according to the formula, the required depth of the excavation would have to be inordinately great, increasing the cost of excavation and adding greatly to the pressures on the lining. The following formula should be used for chambers in loose friable soils (see Figure 6):

$$H_2 \geqq (h_y + r_p - u) \cdot k \quad (9)$$

where k equals the factor of safety, which should be 1.2 to 1.5, depending on the width of the excavation and other structural conditions. At this point it should be noted that when computing the dimensions of the lining, the weight of the column of soil from the top of the chamber to the surface of the ground must be taken into consideration.

In the case of excavation in rock, where no lining is required, the protective depth of the top of the excavated chamber needs only to be not less than the depth of penetration of the projectile plus the effective radius of its explosive force in the given medium (see Figure 7). The minimum depth below the ground surface of the top of the excavated chamber which will suffice to give protection may be found by using the following formula:

$$H_3 \geqq h_y + r_o - u \quad (10)$$

where r_o equals the radius of destruction from the center of the projectile. In Formulas (8), (9), and (10), if the earth layer or medium is of the same kind, h_y may be computed using the following formula:

$$h_y = r \cdot k_1 \frac{p}{d^2} V \cos\alpha. \quad (11)$$

Here,

h_y = depth of penetration of the projectile, shell or bomb, in meters
k_1 = coefficient of penetration (see Table 2, below)
r = coefficient or factor introduced to allow for varied shapes of projectiles; this usually varies from 1.3 to 1.5
p = weight of the projectile, in kilograms
d = diameter of the projectile, in meters
V = velocity of the projectile when it strikes the ground, in meters per second
α = angle of incidence of the projectile at point of impact with the earth surface; i.e., between the vertical and the tangent to the trajectory at point of impact, as indicated in Figure 8
β = angle between tangent and earth surface at point of impact

Example: Find the depth of penetration of a 152-millimeter high-explosive shell. The soil is dense and compact [assuming uniform consistency]. The essential data already known or given are:

r = 1.3
p = 41 kilograms
d = 0.152 meters
V = 250 meters per second
α = 36 degrees
k_1 = 0.0000065 [see Table 2]

Solution: Using Formula (11)

$$h_y = 1.3 \times 0.0000065 \times \frac{41}{(0.152)^2} \times 250 \times 0.809 = 3.2 \text{ m.}$$

Table 2

(k_1 represents the coefficient of penetration; k_2 represents the coefficient of blasting effect; and k_3 represents the coefficient of fragmentation.)

No	Medium (earth, rock, concrete, etc.)	k_1	k_2	k_3
1	Recently broken up fragmented earth	0.000013	1.40	--
2	Mixture of sand and recently fragmented earth	0.000009	1.12	--
3	Compact soil (good for vegetation)	0.0000065	1.08	--
4	Compact clean sand	0.0000045	1.04	--
5	Damp sand, sandy soil	0.0000055	1.00	--
6	Firm hard clay, sandy clay, stony earth	0.000007	0.99	1.93
7	Gravel, mixture of sand and pebbles	0.0000045	0.98	--
8	Clay with sand, petrified earth, loess	0.0000045	0.93	0.9
9	Conglomerates, clay containing marl	0.000004	0.94	1.70
10	Limestone, sandstone, slate	0.000003	0.92	1.17
11	Very hard clay (red)	0.000002	0.88	--
12	Granites, seamless gneiss	0.0000016	0.84	1.0
13	Concrete	0.0000013	0.70	0.52
14	Reinforced concrete	0.00000065 0.0000009	0.60	0.47

To find the depth of penetration of a shell, when the layers of soil between the surface and the roof of the excavated chamber are not of uniform consistency, calculations must be made for the successive layers of disparate consistency by use of the following formulas:

$$h_y' = r k_1' \cdot \frac{p}{d^2} V \cos\alpha$$

$$h_y'' = \ell_1 + (h_y' - \ell_1) \frac{k_1''}{k_1'} \qquad (12)$$

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$$h_y^{n} = \ell_{n-1} + (h_y^{n-1} - \ell_{n-1}) \frac{k_1^{n}}{k_1^{n-1}}$$

where

h_y' = depth of penetration in the type of soil encountered in the first layer

h_y'' = depth of penetration through first layer and in soil of type encountered in the second layer

h_y^n = total depth of penetration through the upper layers and in the type of soil encountered in the nth layer

k_1', k_1'', k_1^{n-1}, k_1^n = the coefficients of penetration of the various dissimilar layers

$\ell_1 \ldots\ldots \ell_{n-1}$ = distance, in each case, from the ground to the under side of each layer

Example: Find the depth of penetration of a 152-millimeter high-explosive shell in a medium of dissimilar layers of earth. The particulars of these layers are as given in Figure 9.

Solution: The depth of penetration of soil of the first layer would be

$$h_y' = 1.3 \times 0.0000065 \times \frac{41}{(0.152)^2} \times 250 \times 0.809 = 3.2 \text{ m.}$$

Since the depth of penetration of soil of the first layer, 3.2 meters, is greater than the actual thickness of this layer, which is $\ell_1 = 0.6$ meters, the shell will penetrate through the first layer and enter the second layer.

The depth of penetration of soil of the second layer would be

$$h_y'' = 0.6 + (3.2 - 0.6) \times \frac{0.0000045}{0.0000065} = 2.4 \text{ m.}$$

Since the depth of penetration of soil of the first and second layers, 2.4 meters, is greater than their combined thickness, $\ell_2 = 1.8$ meters, the shell will penetrate through the first and second layers and enter the third layer.

Depth of penetration of soil of the third layer would be

$$h_y''' = 1.8 + (2.4 - 1.8) \times \frac{0.000004}{0.0000045} = 2.33 \text{ m.}$$

This depth, 2.33 meters, is less than $\ell_3 = 12$ meters; hence, the shell will come to rest in the third layer. The actual depth of penetration is thus found to be

$$h_y = h_y''' = 2.33 \text{ m.}$$

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The value of r_p in Formulas (8) and (9), for a homogeneous medium, is found from this formula:

$$r_p = k_2 \sqrt[3]{C} \tag{13}$$

where r_p is the radius of effectiveness of the explosion of the shell; k_2 is the coefficient of blasting effect (see Table 2); and C is the weight of charge of explosive, in kilograms.

The radius of destructive effectiveness in a medium of dissimilar layers, as the following formulas show, depends on the radius of effectiveness in the successive layers below the point where the shell lodges.

$$\begin{aligned} r_p' &= k_2' \sqrt[3]{C} \\ r_p'' &= y_1 + (r_p' - y_1) \frac{k_2''}{k_2'} \\ r_p^n &= y_{n-1} + (r_p^{n-1} - y_{n-1}) \frac{k_2^n}{k_2^{n-1}} . \end{aligned} \tag{14}$$

In these formulas, r_p' is the radius of destructive effectiveness in the layer nearest the shell; r_p'' is the radius of destructive effectiveness in the second layer; r_p^n is the effective radius of the shell in the nth layer; k_2', k_2'', k_2^{n-1}, k_2^n are the coefficients of blasting effect of the respective layers of earth; and y_1 ...... y_{n-1} are the distances from the center of the projectile to the bottoms of the respective layers, as indicated in Figure 10.

The radius of fragmentation may be calculated from the following formula:

$$r_o = k_3 \sqrt[3]{C} \tag{15}$$

where r_o is the radius of fragmentation; k_3 is the coefficient of fragmentation (see Table 2); and C is the weight of explosive charge in kilograms.

Example: Let the width of the cross section of a concealed chamber, 2a, be 2.3 meters, and its height, b, be 2.4 meters. Assuming it to be built in a layer of clay, find how deep it must be to provide safety from a 203-millimeter high-explosive shell.

Solution: Using Formula (11), the depth of penetration of the shell is

$$h_y = rk_1 \frac{p}{d^2} V \cos \alpha .$$

The known data are:

$r = 1.3$
$k_1 = 0.000007$
$p = 91$ kilograms
$d = 0.203$ meters
$V = 350$ meters per second
$\alpha = 34$ degrees

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Substituting them in the formula, we have:

$$h_y = 1.3 \times 0.000007 \times \frac{91}{0.203^2} \times 350 \times 0.829 = 5.8 \text{ m.}$$

In Formula (13), $k_2 = 0.99$ and $C = 13$ kilograms. Then the radius of destructive effectiveness is

$$r_p = 0.99 \times \sqrt[3]{13} \approx 2.33 \text{ m.}$$

The height of the pressure arch, h_1, is found by using Formula (3b);

$$h_1 = \frac{a + b \tan\left(45 - \frac{\phi}{2}\right)}{f},$$

where the known factors are:

$a = 1.15$ meters
$b = 2.4$ meters
$\phi = 45$ degrees
$f = 1$
tangent $\left(45 - \frac{\phi}{2}\right) \approx 0.414$

Substituting these values in Formula (3b)

$$h_1 = \frac{1.15 + 2.4 \times 0.414}{1} \approx 2.14 \text{ m.}$$

The total protective depth must then be [at least]

$$H_1 = h_y + r_p + h_1 - u$$

$$H_1 = 5.8 + 2.33 + 2.14 - 0.102 = 10.17 \text{ m.}$$

The value used for u is one half of the diameter of an ordinary shell; d equals 0.203 meters.

[The text ends at this point. However, in the last example cited, no mention is made of the factor of safety, nor is there any demonstration of the manner in which the coefficient of fragmentation of the medium is introduced into the problem.]

[Appended figures follow:]

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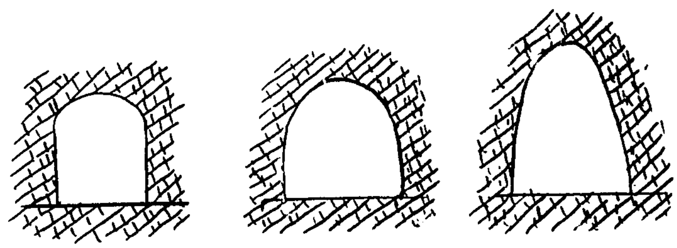

Figure 1

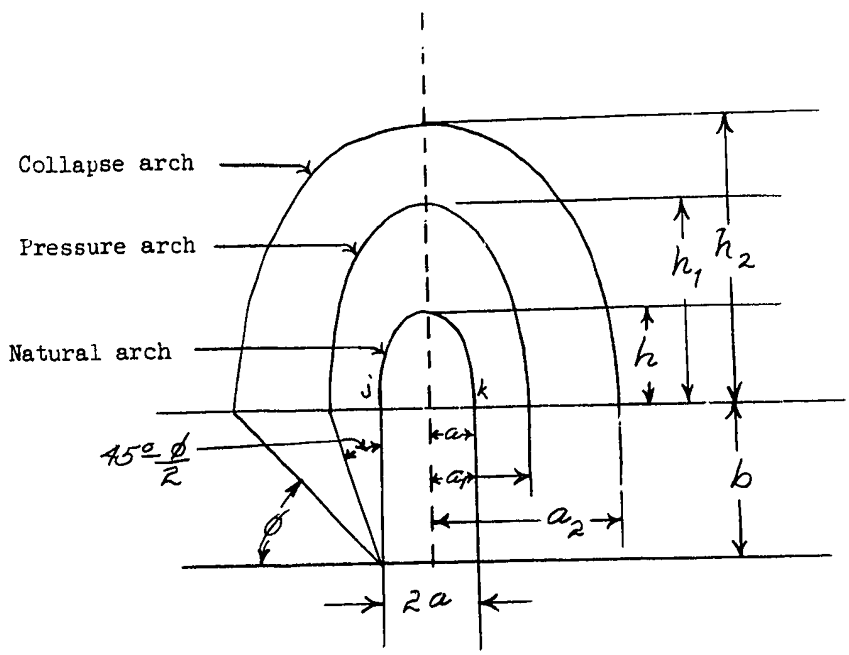

Figure 2

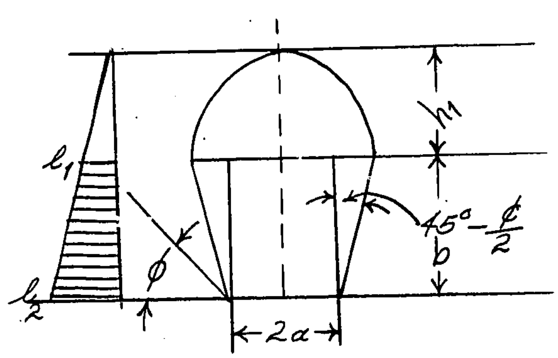

Figure 3

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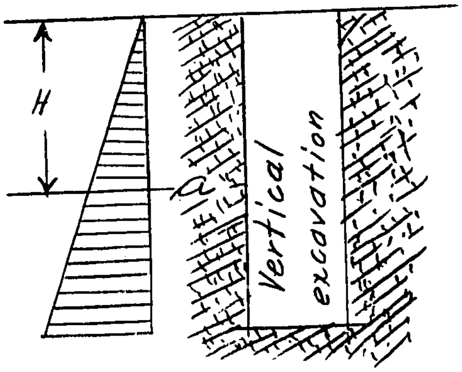

Figure 4a. Homogeneous Earth

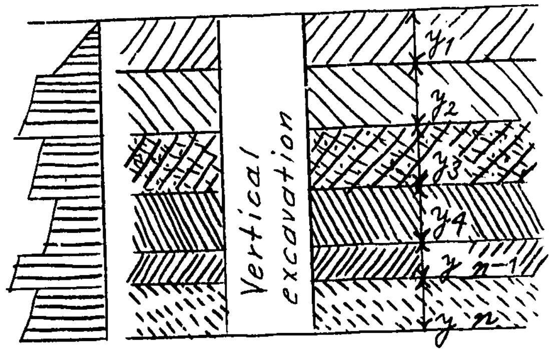

Figure 4b. Nonhomogeneous Earth

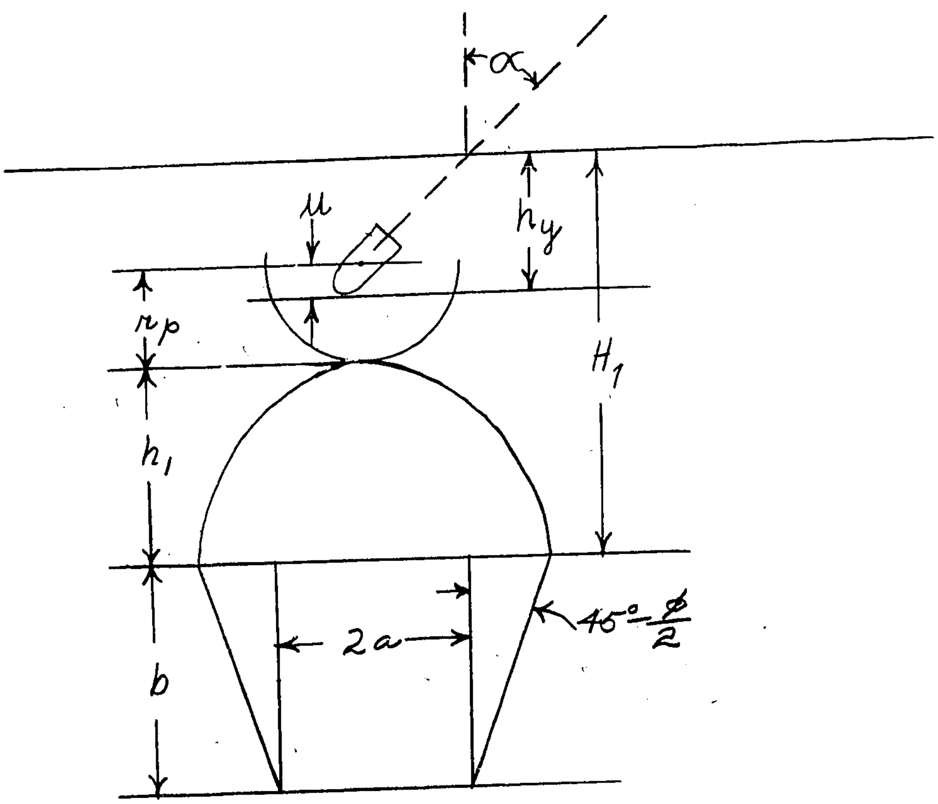

Figure 5.

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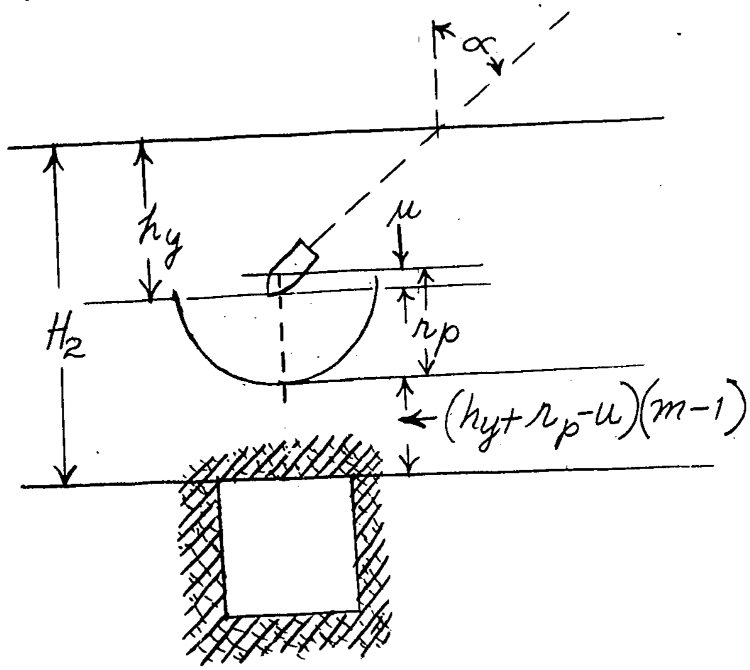

Figure 6

[Probably m is here wrongly written for k, which should have a value of from 1.2-1.5.]

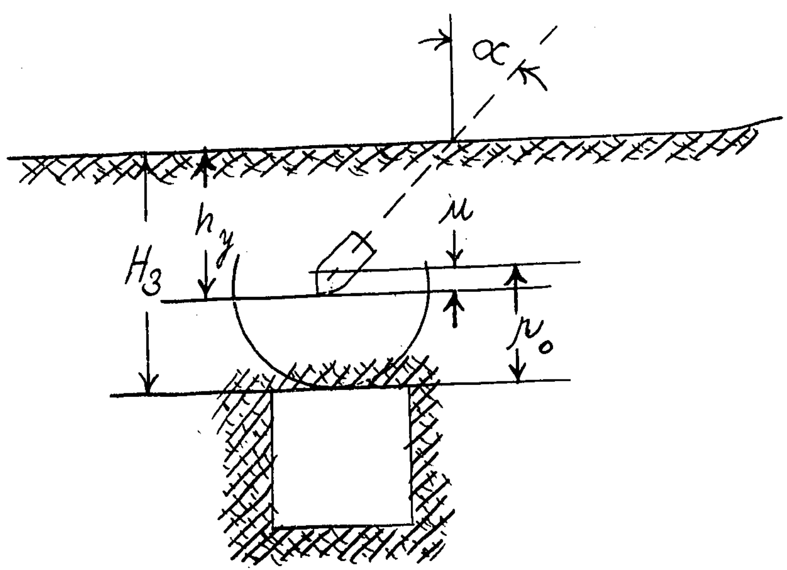

Figure 7

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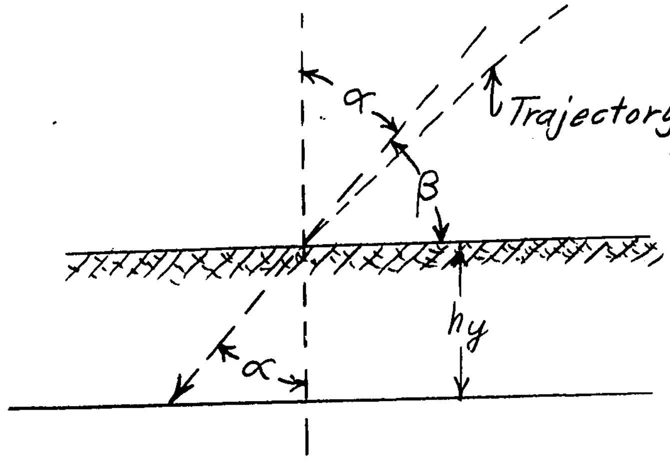

Figure 8

Ground Surface	Nature of Soil	Symbol	Thickness of Layer (meters)	Depth to Bottom of Layer	Coefficient of Penetration	Layer No
	Black soil		0.6	$l_1 = 0.6$	$k_1 = 0.0000065$	1
	Sandy soil		1.2	$l_2 = 1.8$	$k_1 = 0.0000045$	2
	Clay containing marl		10.2	$l_3 = 12.0$	$k_1 = 0.0000040$	3

Figure 9. Circumstances and Characteristics of Earth Layers

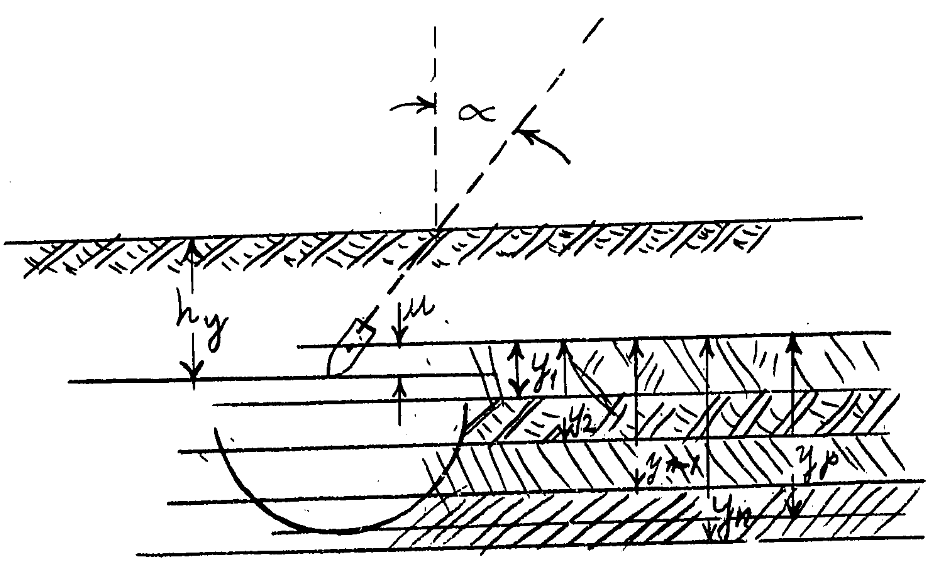

Figure 10

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